

Cratered cobbles in Triassic Buntsandstein conglomerates in northeastern Spain: An indicator of shock deformation in the vicinity of large impacts

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ABSTRACT

Quartzite cobbles in Lower Triassic Buntsandstein conglomerates from northeastern Spain display unusual millimeter- to centimeter-sized circular craters, commonly having central mounds and surrounded by radial fractures. The conglomerates are also marked by intense fracturing down to microscopic scale. These features have traditionally been attributed to tectonic compression and pressure dissolution at cobble contacts. Sections through the cratered cobbles reveal pervasive internal fracturing, segments detached along concave spall fractures, and zones marked by quartz grains with planar deformation features. Comparison with results of impact experiments on artificial conglomerates suggests that these features were produced by internal accelerations, grain collisions, and spallation related to shock-wave propagation through inhomogeneous deposits. The proximity of the outcrops to the Azuara and proposed Rubielos de la Cérda impact structures suggests that shock deformation of conglomerates can provide an easily recognizable regional impact signature.

Keywords: impact, shock, conglomerates, spallation, Triassic, Azuara impact structure.

INTRODUCTION: CRATERED AND FRACTURED COBBLES

In northeastern Spain, deposits of Triassic basal Buntsandstein conglomerates to several tens of meters in thickness (Fig. 1) contain cobbles of Paleozoic quartzite that are covered with surface craters of millimeter to centimeter size and are intensely fractured. In the past, these craters and related deformation of the cobbles have been explained by tectonic compression and pressure dissolution (e.g., Instituto Tecnológico Geominero de España, 1991). The recent discovery of evidence for two large impact structures in the region—the Azuara structure (Ernstson et al., 1985) and the proposed Rubielos de la Cérda structure (Ernstson et al., 1994) (Fig. 1)—led to a re-investigation of the cratered and fractured conglomerates as possible indicators of impact-induced deformation, supported here by new impact experiments on artificial conglomerates where the features were simulated.

The cratered cobbles have diameters from ~1 to 20 cm and can best be studied loose in the field where they have become separated from the sandy matrix by weathering. The craters (Fig. 2, A and B) are circular to elongate in outline and are up to 35 mm in diameter and up to 7 mm in depth. They are usually flat or bowl-shaped and commonly have a distinct central mound. Many craters show radial fracturing extending outward to several crater diameters (Fig. 2A), and in some cases frac-

turing is accompanied by crushing of the cobble (Fig. 2, B and C).

Sections through the cratered cobbles show that the prominent radial surface fractures form conical patterns similar to concussion

fractures or Hertzian cones (Kieffer, 1971) (Fig. 2C). Thin-section analysis reveals a system of radial and concentric fractures below the craters, and the fractures are commonly open, even in the central mound areas, indicating a tensional origin. Distinct bright halo zones occur beneath the craters (Fig. 2C) and quartz grains in these zones commonly exhibit decorated planar deformation features (Fig. 3A); some grains display multiple sets indicating shock pressures of ~10 GPa (Stöffler and Langenhorst, 1994). Thin sections also show that segments of the cobbles have become detached along concave fractures (Fig. 4).

In outcrop, the cratered conglomerates show closely spaced (on the millimeter scale) subparallel fracturing (Fig. 2D). The strike of the fracturing is rather homogeneous within a single outcrop, but strike directions in sections only a few hundred meters apart may differ significantly, and there is no regional trend. A second set of fractures, subordinate and rough-

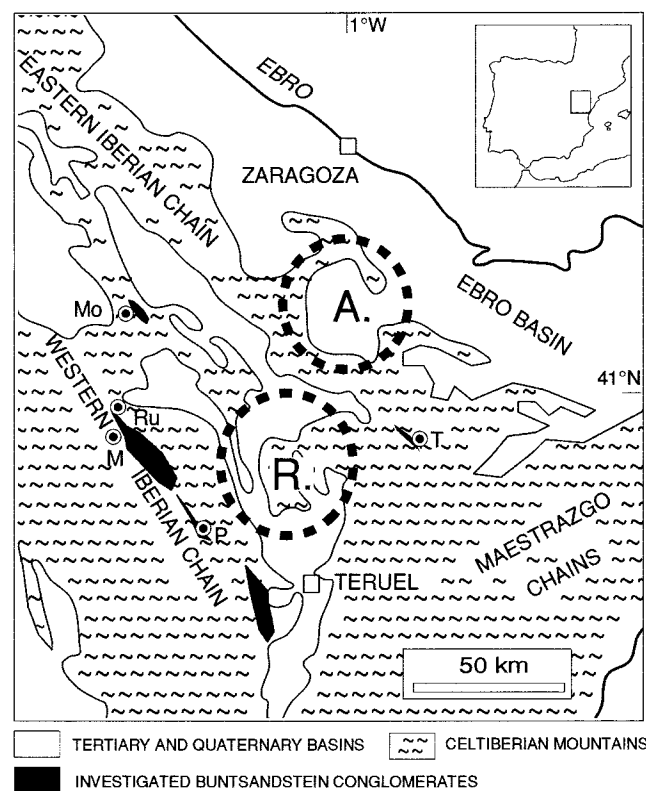


Figure 1. Location map showing outcrops of Buntsandstein conglomerates exhibiting cratered and fractured cobbles. A—Azuara impact structure; R—proposed Rubielos de la Cérda impact structure. M—Molina de Aragón; Mo—Monasterio de Piedra; P—Peracense; Ru—Rueda de la Sierra; T—Torre de las Arcas.

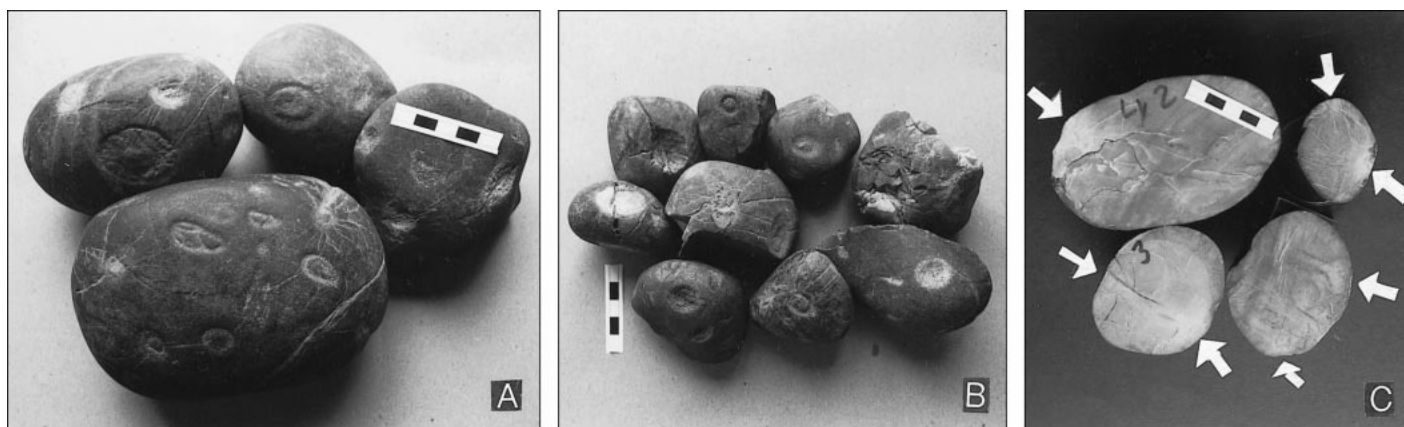


Figure 2. Macroscopic aspects of Buntsandstein cobbles. A and B: Cratered quartzite cobbles. C: Halo zones beneath craters (arrows) and typical internal fracturing (centimeter scale in A–C). D: Cobbles in outcrop showing subparallel fracturing (field of view is 40 cm wide).



Figure 3. A: Decorated planar deformation features (PDFs) in quartz grains from zone below cobble craters. B: Subparallel microfractures in quartz grains from cratered quartzite cobbles (photomicrographs, crossed polarizers; width of field of view is 440 μm in A and 220 μm in B).

ly normal to the first set, is observed in some outcrops. The fractures are commonly irregular, curved, and bifurcated and do not have the character of systematic joints. They apparently formed in opening mode and are thus tensional. Thin sections reveal sets of subparallel intergranular microfractures with spacings down to a few micrometers (Fig. 3B).

ORIGIN OF CRATERED COBBLES BY PRESSURE SOLUTION?

Most previous workers have ascribed the cratering of the quartzite cobbles to pressure dissolution at the contacts between mineral grains, which takes place when the external pressure exceeds the hydraulic pressure of

pore fluids and material is dissolved and removed from the contact zone (e.g., Mosher, 1981; Bjørkum, 1996). In cases of documented pressure solution, cobbles commonly become interpenetrating, but the internal fabric of the clasts is largely unaffected (Mosher, 1981). Individual quartzite pebbles may show evenly spaced intrapebble shear fractures and extension fractures oriented normal to the long axes of the pebbles, but intense fracturing is rare (Mosher, 1981). Microstylolites have been reported from within the pebbles and at pebble-pebble contacts, and material removed by solution commonly migrates to areas of lower stress and precipitates within the matrix and as fracture fillings (Mosher, 1981;

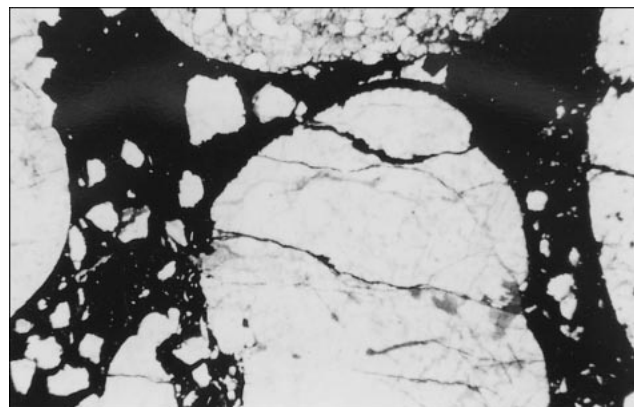


Figure 4. Photomicrograph of in situ pebble from Buntsandstein conglomerate showing detachment of segment along concave fractures (spall) that forms surficial crater (matrix is opaque from iron hydroxide precipitation). Field of view is 6.5 mm wide.

Björkum, 1996). Residual material is also concentrated in selvages at cobble contacts, and in quartzite cobbles, long pressure shadows of fibrous quartz are commonly produced in the direction of minimum compressive stress (Mosher, 1981).

None of these features was seen in thin-section inspection of the Buntsandstein cobbles. By contrast, our analyses show a number of features that are not compatible with a pressure-solution origin. Open fractures beneath the craters suggest tensional stresses rather than compression in these zones, and the central mounds are commonly cut by open fractures and rise well above the rim of the craters. The microfracture haloes and quartz grains with planar deformation features beneath the craters (Figs. 2C and 3) have not been described in rocks affected by pressure solution.

The subparallel and closely spaced tensile fracturing of the cobbles might be interpreted tectonically as having developed parallel to the maximum compressive stress. Eidelman and Reches (1992) reported that such fractures can develop in poorly cemented cobbles even during compression, and thus could be indicators of regional tectonic stresses. In most tectonic situations, however, preferential shear stress in the matrix leads to displacement and rotation of the cobbles instead of fracturing (Mosher, 1981), and the closely spaced fractures in the Buntsandstein deposits (Figs. 2D and 3B) are quite different from typically more widely spaced tectonic fractures.

IMPACT SPALLATION AND FRACTURING

The Buntsandstein conglomerates occur in the vicinity of two reported impact structures.

The ~40-km-diameter Azuara structure (mid-Tertiary) (Ernstson et al., 1985) is located ~50 km south of Zaragoza in northeastern Spain (Fig. 1). Further regional studies led to the proposal of a companion ~40-km-diameter Rubielos de la Cérida impact structure (Fig. 1) with a distinct central uplift (~15 km diameter), impact-melt rocks, and shock metamorphism (Ernstson et al., 1994).

As impact shock waves pass through inhomogeneous rocks, such as conglomerates, new wave fronts and wavelets develop, splitting the energy and leading to highly localized concentrations of intense stress (Rinehart, 1968). Spallation takes place when the compressive shock pulse impinges on a free surface or boundary between materials of different impedances (impedance is the product of density and sound velocity) where it is reflected as a rarefaction pulse. The reflected tensile stresses lead to detachment of a spall or series of spalls (Rinehart, 1968; Melosh, 1989). The fracturing and cratering in the Buntsandstein cobbles indicate a combination of compressive and extensional stresses that are diagnostic of spallation (Rinehart, 1968), and spallation processes are especially common in the near-surface target zone of impacts (Melosh, 1989).

The Buntsandstein cobbles are densely packed within the mostly interstitial matrix, so that collisions among the cobbles, with resulting concussion and fracturing, would have occurred as they were accelerated by high-velocity mass flow behind the shock front. Comparable processes were proposed in a model of shock effects in the Coconino Sandstone at Meteor Crater, Arizona, where weakly shocked rocks display quartz grains with net-

works of radial concussion fractures emanating from grain-contact surfaces (Kieffer, 1971). In the Buntsandstein cobbles, Hertzian fracturing and spallation fracturing may have acted simultaneously to produce the characteristic central mounds (Fig. 4). Subsequent interaction among the cobbles, probably at reduced particle velocities, could explain the many smaller pits and grooves on cobble surfaces.

Macroscopic and microscopic subparallel fracturing has been reported from several terrestrial impact structures, including Vredefort (Albat and Mayer, 1989), Steinheim (Reiff, 1979), Gosses Bluff (Milton, 1977), and Azuara (Ernstson et al., 1985). Microscopic subparallel intergranular fractures occur at the Deep Bay crater (Robertson et al., 1968) and the Ries structure (Chao and El Goresy, 1977), and similar microfractures were formed in granodiorites shocked in the Hardhat nuclear experiment (Short, 1968). Distinct bright halo zones in lunar micrometeorite craters, produced by microfracturing (Hörz et al., 1971), are similar to the halo zones beneath the cobble craters.

IMPACT EXPERIMENTS ON SYNTHETIC CONGLOMERATES

Features similar to those observed in the deformed Buntsandstein cobbles have been produced in high-velocity impact experiments (e.g., Curran et al., 1977; Lange et al., 1984; Polanskey and Ahrens, 1990). In order to further test whether the features seen in the Buntsandstein cobbles could be produced by impact deformation, we performed new shock experiments at the Fraunhofer Institute for High-Speed Dynamics (Ernst-Mach-Institut)

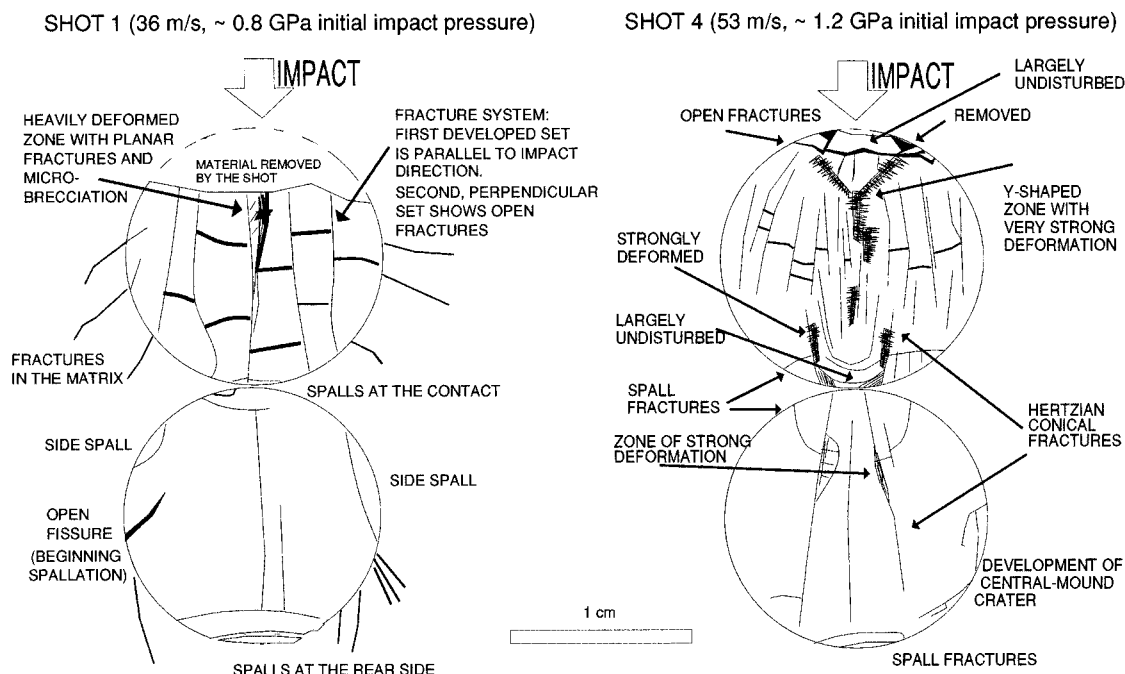


Figure 5. Deformations in quartz spheres (1.4 cm in diameter) from impact experiments on synthetic conglomerates (see text). Shown are results of shot 1 (~0.8 GPa) and shot 4 (~1.2 GPa). Drawn from microscopic observations.

in Freiburg, Germany. A single-stage powder gun was used to accelerate steel projectiles of truncated-cone shape. As targets, we used two quartz spheres (rock crystal, diameter 14 mm) in contact, embedded in a synthetic epoxy matrix. Five shots were performed with impact velocities in the range of 25 to 115 m/s, corresponding to impact pressures between 0.55 and 2.5 GPa. The recovered samples were cut in half, thin sections were made in the plane of cut, and drawings were made (Fig. 5).

Shot 1 (36 m/s; 0.8 GPa) resulted in loss of the upper part of the targeted sphere. The lower half of the sphere is characterized by two sets of roughly perpendicular fractures (Fig. 5). The first-formed fracture set is oriented parallel to the impact trajectory, whereas the open fractures of the second-formed set developed perpendicular to the impact. The axis of the sphere is marked by a narrow, sharply defined zone of intense deformation with planar fractures (cleavage) and microbrecciation. The lower sphere is less deformed internally, but at least five spalls are distributed over the surface of the sphere (cf. Fig. 4).

The spheres recovered from shot 4 (53 m/s; 1.2 GPa) are heavily damaged in their interiors (Fig. 5). The zone at the site of direct impact has been retained, but a spall was formed by detachment along an open concave fracture surrounded by a circular moat where material was removed. A similar pattern can be observed at the contact with the lower sphere. A general fracture pattern (as discussed for shot 1) also developed in the targeted sphere, similar to that seen in the Buntsandstein cobbles (Fig. 4). Thin sections show that the interior of the targeted sphere contains conical zones marked by microbrecciation and reduced refractive index, planar fractures (cleavage), mosaicism, small patches (~100 μm size) of isotropization, and incipient formation of planar deformation features.

DISCUSSION AND CONCLUSIONS

The quartz spheres in our experimental impacts and the Buntsandstein cobbles show striking similarities. The common factor is the presence of roughly spherical bodies embedded in a matrix of material with lower wave impedance, and the experiments indicate that the spallation process can be very effective even in the case of low impedance contrast and relatively low impact velocities. This suggests that the strong impedance contrasts in the Buntsandstein conglomerates (very dense quartzite cobbles in a sandy matrix) might have led to spallation at lower shock conditions than in our experiments.

Shock-wave velocities and pressures in the

vicinity of large impacts are poorly known because of uncertain initial conditions and the complex propagation conditions in geologic targets (Melosh, 1989). The initial deformation of the conglomerates by the shock wave should result in a peak particle velocity immediately behind the shock front. This velocity is estimated to decrease as roughly $1/r^2$ (r = radial distance from the impact point; maximum particle velocity near the impact site is ~0.5 times the impact velocity) (Melosh, 1989). After the passage of the shock-wave front, the peak particle velocity at any site reduces by 1/3 to 1/5, defining the maximum velocity of the shock-initiated excavation mass flow (Melosh, 1989).

For a 20 km/s impact, peak particle velocities of 10 km/s near the impact site ($r = 2$ km) may be reasonable. From the $1/r^2$ decay, we compute peak particle velocities ranging from ~40 m/s at 30 km to 4 m/s at 100 km distance, the range of cratered-cobble localities from the Rubielos de la Cérida structure (25 km for Torre de las Arcas to ~60 km for localities southwest of Teruel) (Fig. 1). The latter deposits are also within ~100 km from the center of the Azuara structure.

The particle velocities computed for the 30–60 km radial distance from the proposed Rubielos de la Cérida impact site are about the same as impact velocities in our impact experiments. The longer duration of the natural impact shock, and reverberations from the large number of cobbles in close contact, should have produced even greater deformation effects in the Buntsandstein conglomerates as compared with our experiments. Our results suggest that the cratering and intense fracturing in the Buntsandstein conglomerates can be explained by passage of impact shock waves through these inhomogeneous deposits, and such features may provide a diagnostic regional signature for impact cratering.

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